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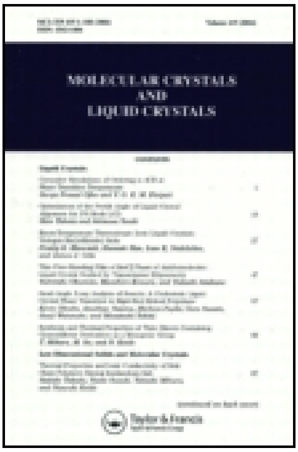

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Voltage Controlled Light Transmittance in Polymer Dispersed Liquid Crystals

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VOLTAGE CONTROLLED LIGHT TRANSMITTANCE IN POLYMER DISPERSED LIQUID CRYSTALS

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Abstract

In recent papers we have studied the optical phase shift induced by a Polymer Dispersed Liquid Crystal (PDLC) sample subjected to a low frequency electric field. In the framework of the droplet model for the PDLC we have shown that the description of the sample by means of three (molecular, droplet and sample) order parameters and two (a surface elastic constant and a characteristic voltage constant) sample related parameters is able to give a good agreement with experimental data. In this paper we present further applications of the model showing how applied voltages controls light scattering.

1 Introduction

The growing interest on Polymer Dispersed Liquid Crystals (PDLC) is due to the wide range of possible applications: from large scale flexible displays to windows with controlled transparency to thermal sensors and devices for optical processing.

A PDLC is made of liquid crystal microdroplets embedded in a (usually isotropic) polymeric matrix. Depending on technical tips, the droplets, randomly dispersed in the polymer, may have a size close to the visible light wavelength, thus producing a strong light scattering.

It is well known that the interest for such materials is due to the possibility to control the light scattering through the application of an electric field. Droplets have a strong optical anisotropy, depending on liquid crystal's orientation inside them, and therefore, on applied electric field. So it is possible to reduce the refractive index mismatching between droplets and polymeric matrix, thus switching the sample from an opaque to a transparent state[1].

Moreover, from a fundamental point of view PDLC are interesting because many physical properties of liquid crystal are strongly influenced by the confinement of the material in a small cavity.

In previous papers[2, 3] we have reported the study of the optical phase shift induced by a PDLC sample when a low frequency electric field is applied to it. We have shown that a theoretical model based on the description of the sample by means of three (molecular S, droplet S_d and sample S_f) order parameters and two (an elastic constant per unit area K_d and a characteristic voltage V_d) sample related parameters is able to give a good agreement with experimental data.

In this paper we present further application of the model to the Anomalous Diffraction Approach (ADA) scattering theory[4] to evaluate light transmission in a PDLC sample.

2 The PDLC model

Droplets reorientation in a PDLC can be described[5, 2] by means of the following three (molecular, droplet and sample) order parameters:

$$\begin{aligned} S &= \left\langle P_2(\hat{\mathbf{n}} \cdot \hat{\mathbf{l}}) \right\rangle \\ S_d &= \left\langle P_2(\hat{\mathbf{N}}_d \cdot \hat{\mathbf{n}}) \right\rangle_{droplet} \\ S_f &= \left\langle P_2(\hat{\mathbf{E}} \cdot \hat{\mathbf{N}}_d) \right\rangle_{sample} \end{aligned} \tag{1}$$

where P_2 is the second order Legendre polynomial, $\hat{\mathbf{l}}$ is the molecular axys, $\hat{\mathbf{n}}$ is the nematic director, and $\hat{\mathbf{N}}_d$ is the droplet director (i.e. the mean value of $\hat{\mathbf{n}}$ inside each droplet) and $\hat{\mathbf{E}}$ is the low frequency electric field director.

The sample order parameter can be computed from the following implicit relations:

$$S_f = \frac{1}{4} + \frac{3}{16}\frac{e_a^2+1}{e_a^2} + \frac{3}{32}\frac{(3e_a^2+1)(e_a^2+1)}{e_a^3}\ln\left|\frac{e_a+1}{e_a-1}\right| \tag{2}$$

$$e_a(S_f) = E\sqrt{\frac{3\,\epsilon_p\, v_{lc}}{\epsilon_{lc}+2\epsilon_p - v_{lc}(\epsilon_{lc}-\epsilon_p)}\frac{\epsilon_{\|}-\epsilon_{\perp}}{K_d}} \tag{3}$$

$$\epsilon_{lc} = \epsilon_{\perp} + \frac{1}{3}(1+2SS_dS_f)(\epsilon_{\|}-\epsilon_{\perp}) \tag{4}$$

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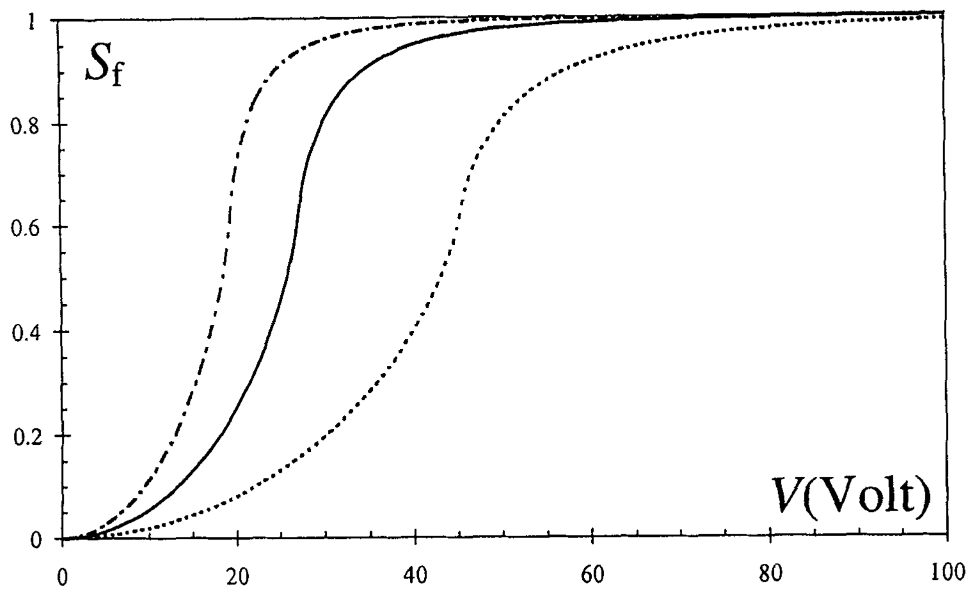

Figure 1: The sample order parameter S_f vs. the applied voltage for three values of the elastic constant K_d: $11.0 N/m^2$ (dash-dotted line), $4.0 N/m^2$ (full line) and $2.0 N/m^2$ (dashed line). The values of other parameters are shown in Tab. 1

where v_{lc} is the volume fraction of liquid crystal in the sample, ϵ_p is the polymer dielectric permittivity, $\epsilon_{\parallel}$ and $\epsilon_{\perp}$ are the liquid crystal dielectric permittivities and K_d is an elastic constant per unit surface[3] (units: Newton per square meter) taking into account the torque which, after the field is switched-off, produces relaxation of the droplets to their original orientation.

In this model the only order parameter affected by the applied voltage is S_f. Fig. 1 shows the behaviour of S_f versus the applied voltage for several values of the elastic constant K_d.

3 PDLC transmittance

For droplet radii $R_d \geq 0.1 \mu m$ the scattering cross section can be computed following the Anomalous Diffraction Approach (ADA)[4, 5]

$$\sigma_{ADA} = \frac{\pi R_d^2}{2} \left(\frac{4\pi}{\lambda} R_d \right)^2 \left(\frac{n_{de} - n_{do}}{n_p} \right)^2$$

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Liquid Crystal (E7)

$T_{NI} = 54.5°C$ (experimental value in our PDLC sample)
$\epsilon_{\parallel} = 7.2\ \epsilon_0$ (at $T = 20°C$)
$\epsilon_{\perp} = 6.0\ \epsilon_0$ (at $T = 20°C$)
$n_e = 1.716$ (at $T = 20°C$)
$n_o = 1.513$ (at $T = 20°C$)

Polymer (EPON 815)

$\epsilon_p = 5\ \epsilon_0$
$n_p = 1.55$

Sample

$d_s = 8\mu m$
$v_{lc} = 0.7$
$R_d = 200nm$
$S_{d0} = 0.7$

Probe beam

$\lambda = 632.8nm$

Table 1: Values assumed for various parameters

$$\left[\left(\frac{n_p - n_{do}}{n_{de} - n_{do}}\right)^2 - \frac{2}{3}\frac{n_p - n_{do}}{n_{de} - n_{do}}(1 - S_f) + \frac{4}{105}\left(7 - 10S_f + 3\tilde{S}_f\right)\right] \quad (5)$$

here

$$\tilde{S}_f = \frac{7}{12} + \frac{5}{12}S_f - \frac{35}{32e_a^2}\left[\frac{2}{3} + \frac{(e_a^2-1)^2}{4e_a^2} - \frac{(e_a^2+1)^2(e_a^2-1)}{8e_a^3}\arctan\left(\frac{2e_a}{e_a^2-1}\right)\right] \quad (6)$$

n_p is the polymer refractive index; n_{do} and n_{de} are the ordinary and extraordinary refractive indices of the (anysotropic but homogeneous) droplets.

In former papers[5], droplet refractive indices were assumed to be the same as liquid crystal ones ($n_{do} = n_o$, $n_{de} = n_e$), while here we improve such approximation with the use of the calculated droplet's refractive indices.

The transmitted light intensity ratio is

$$I/I_0 = \exp(-N_v\, \sigma_{ADA}\, d_s) \quad (7)$$

where d_s is sample thickness and $N_v = 3v_{lc}/4\pi R_d^3$ is the number of droplets per unit volume.

Substitution of $S_f(V)$ into previous equations allows the calculation of the scattering cross section σ_{ADA} and, finally, of the sample transmittivity vs. the applied voltage, as shown in Fig. 2.

Droplet model allows to compute ordinary and extraordinary droplet refractive indices[2]:

$$n_{do} = \frac{2}{\pi}n_o\; F\left(\frac{\pi}{2}, \frac{1}{n_e}\sqrt{\frac{2}{3}(n_e^2 - n_o^2)(1 - S_d)}\right) \quad (8)$$

$$n_{de} = \frac{n_o\, n_e}{\sqrt{\frac{2}{3}(n_o^2 - n_e^2)S_d + \frac{1}{3}(n_o^2 + 2n_e^2)}} \quad (9)$$

where $F(\theta, m)$ is the complete elliptic integral of the first kind. Therefore in our model the droplets refractive indices depend on the value of the droplet order parameter S_d. In Fig. 3 we show n_{do} and n_{de} vs. S_d.

As shown in Fig. 4 the model is unable to fit experimental data for any given value of S_d, so we must drop out the hypothesis of constant S_d. Introducing a dependence of S_d on the applied voltage[3]

$$S_d(V) = 1 - (1 - S_{d0})\exp(-V/V_d) \quad (10)$$

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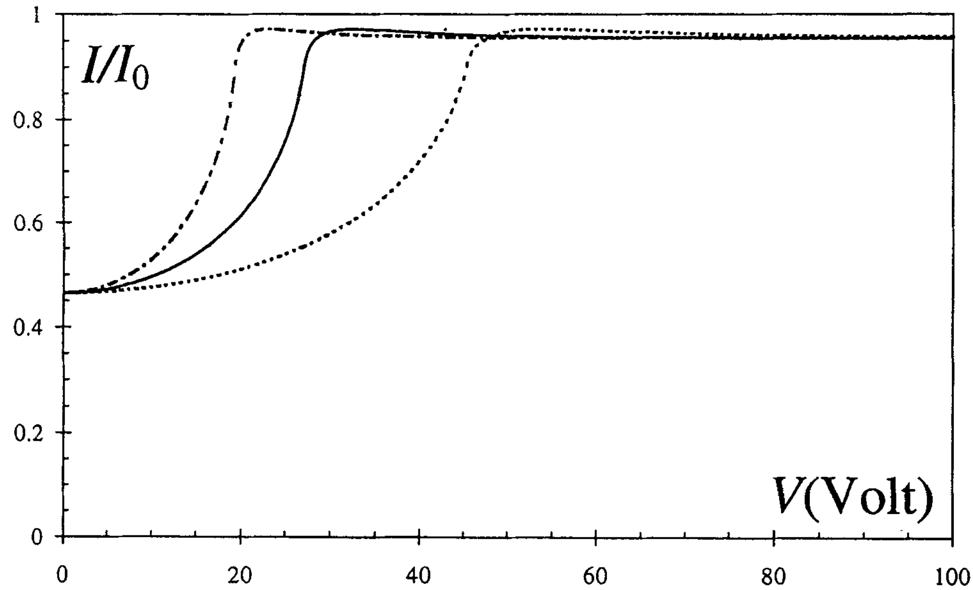

Figure 2: The sample transmittance I/I_0 vs. the applied voltage V. Each curve corresponds to a different value of K_d as in Fig. 1. Here droplet refractive indices are assumed to be the same as liquid crystal ones (i.e. $n_{do} = n_o$, $n_{de} = n_e$).

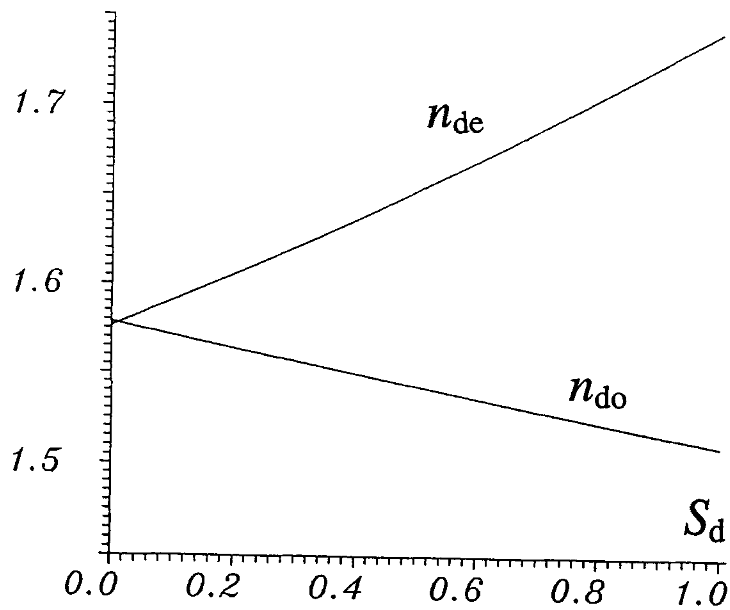

Figure 3: The droplet ordinary and extraordinary refractive indices vs. the droplet order parameter S_d.

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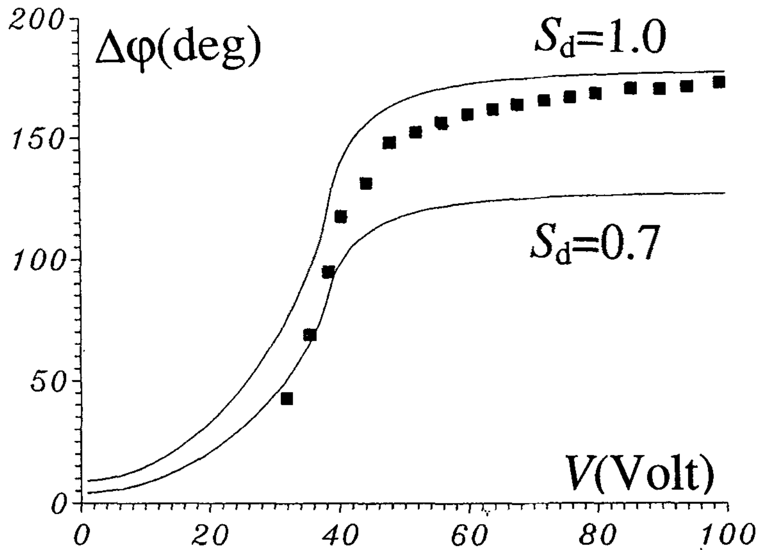

Figure 4: Measured optical phase shift vs. applied voltage compared with the values obtained using the model with constant S_d. The values used are $S_d = 0.7$ and $S_d = 1.0$. Incidence angle is $\theta_i = 20\,\text{deg}$.

we have obtained a good agreement between model and experimental data as can be seen in Fig. 5. V_d (units: Volt) is a sample related parameter taking into account the voltage dependence of the alignment of liquid crystal molecules inside each droplet. As a consequence also n_{do} and n_{de} are no more constant. Substitution into eq. (5) allows the calculation of the sample transmittance.

4 Results and conclusions

Let us examine how the order parameters and the sample characteristics affect the light transmittance.

A comparison of Fig. 2 with Fig. 1 shows that S_f, and therefore K_d, is the main responsible for the threshold voltage (i.e the voltage corresponding to the opaque to transparent switching).

In Fig. 6 we can see the behaviour of S_d vs. the applied voltage while Fig. 7 shows the corresponding values of the droplet refractive indices and Fig. 8 shows the normalized values of the transmitted intensity.

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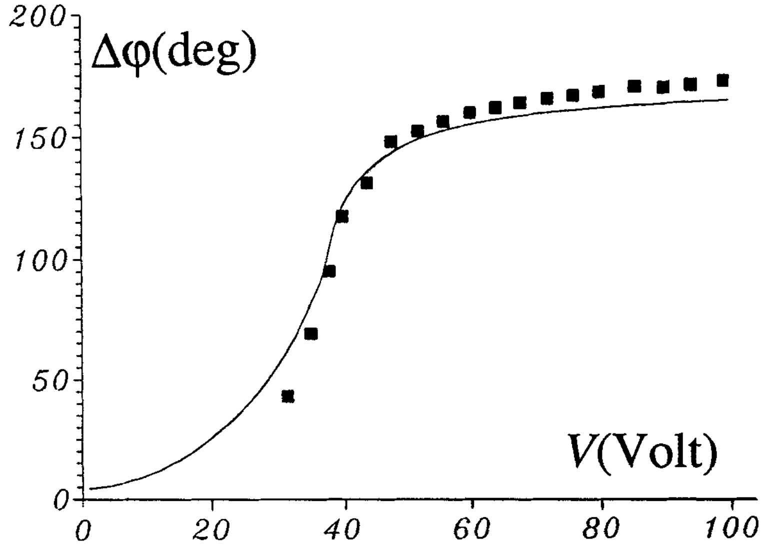

Figure 5: Measured optical phase shift vs. applied voltage compared with the values obtained using the model with constant $S_d(V)$. Incidence angle is $\theta_i = 20\,\mathrm{deg}$.

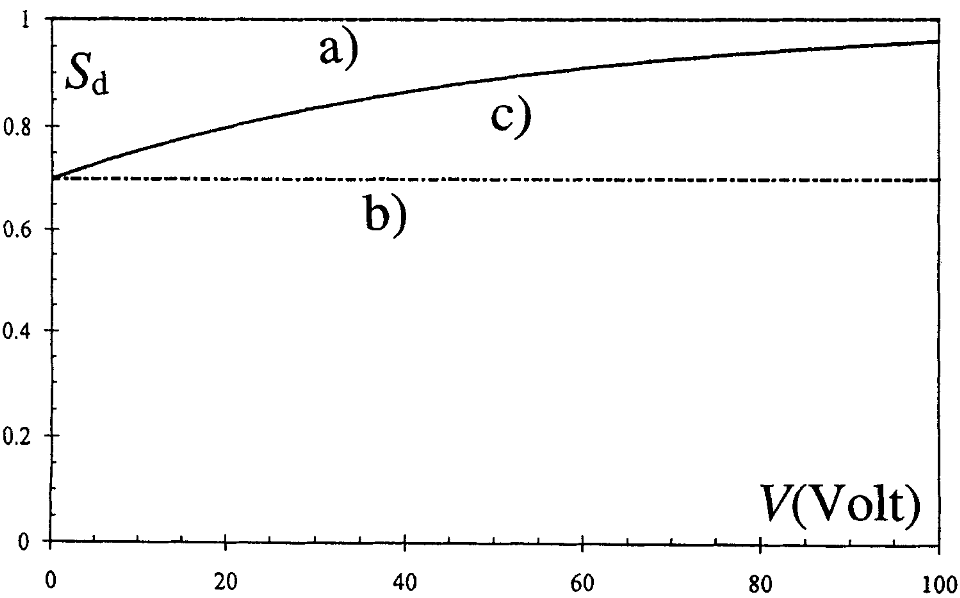

Figure 6: Droplet order parameter S_d vs. applied voltage V.

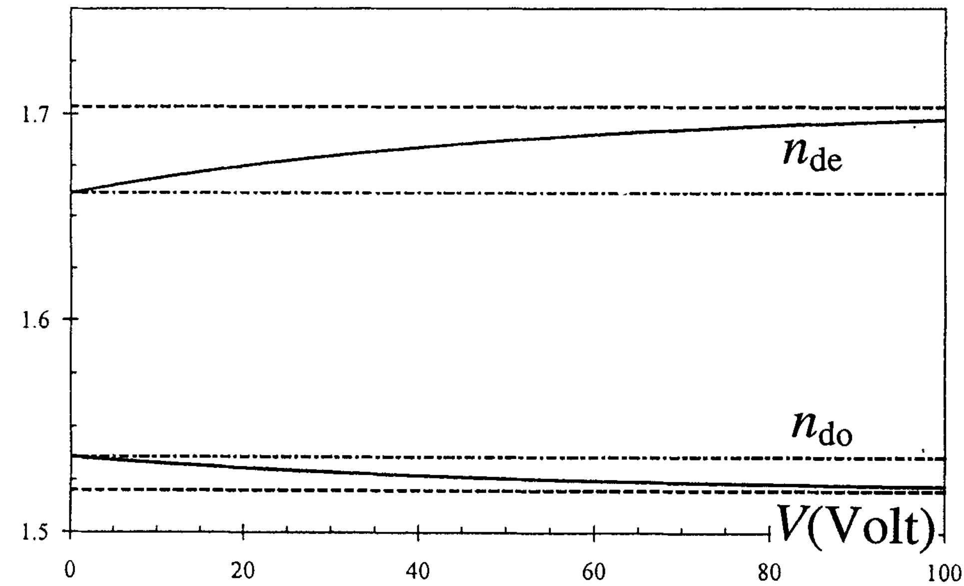

Figure 7: Droplet refractive indices vs. applied voltage.

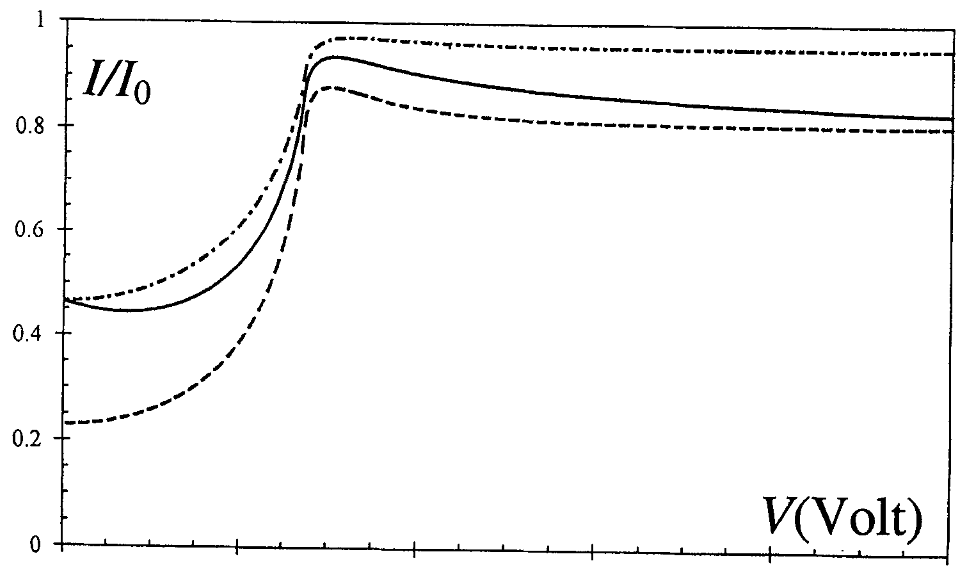

Figure 8: The sample transmittance I/I_0 vs. the applied voltage V.

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The droplet order parameter S_d takes into account the molecular alignment inside each droplet. Three cases are shown:

a) $[S_d = 1]$, dashed lines: liquid crystal molecules into each droplet are always fully aligned along the droplet director; droplet refractive indices are the same as liquid crystal ones and therefore are not affected by applied field.

b) $[S_d = S_{d0}]$, dash-dotted lines: liquid crystal molecules into each droplet are "frozen", so that when an external field is applied each droplet rotates as a whole (the value $S_{d0} = 0.7$ is the usual one for bipolar droplet configuration); droplet refractive indices are not the same as liquid crystal ones but are not affected by applied field.

c) $[S_d = S_d(V)]$, full lines: molecules alignment inside each droplet increases with increasing applied field so that droplet refractive indices depend on applied field.

In cases a) and b) the transmitted intensity reaches its saturation value slightly above the threshold voltage. In case c) the transmitted intensity changes above the threshold because molecules modify their alignment inside droplets even after droplets are well aligned to external field.

The sample order parameter S_f, affected by the sample related characteristic elastic constant K_d, determines the threshold value of the PDLC opaque to transparent switching. The droplet order parameter S_d, affected by another sample related parameter V_d, determines the transmittance behaviour for applied voltage far above threshold. Both parameters (K_d and V_d) are functions of the temperature, so that further experimental data are required to improve the model.

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